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Renewable and Sustainable Energy Reviews
8 (2004) 461–481

RENEWABLE & SUSTAINABLE ENERGY REVIEWS

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Progress in energy utilization from agrowastes in Taiwan

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Received 17 December 2003; accepted 17 December 2003

Abstract

Taiwan is a high energy-importing nation with more than 95% of its energy supplied by imported fuels. Environmental pollution and greenhouse gas emissions are becoming significant environmental issues. In this regard, renewable energy like waste-to-energy are thus becoming attractive due to the energy policy for the sustainable development and environmental pollution mitigation in Taiwan. The objective of this paper is to present an updated overview of energy utilization from mass agrowastes in industries. The description is thus centered on new/revised promotion legislation/regulations especially concerning the agro-waste-to-energy in the measures of environmental protection and economic/financial incentives. The Statute for Renewable Energy Development is being enacted to further enhance and promote the green energy utilization, which is also addressed in the paper. Finally, we present the biomass energy utilization of three mass agrowastes (i.e. bagasse and rice husk from mills, and piggery wastes from swine farms) in progress.

Keywords: Agrowaste; Energy utilization; Regulation; Promotion measure; Energy policy

Contents

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1364-0321/$ - see front matter
doi:10.1016/j.rser.2003.12.008

1. Introduction

Since the energy crisis in the 1970s, the energy utilization from biomass resources has received much attention. The energy in biomass (called biomass energy) from plants, animals (that eat plants or other animals) or wastes that they produce, originally comes from solar energy through the photosynthesis process. The energy supply from domestic waste materials is especially noted in that it not only eliminates the environmental pollution, but also saves costs on fuel usage in the manufacturing/processing industries. Of the many energy productions from waste materials, agricultural wastes or agrowastes seem to be particularly attractive based on bioresource sustainability, environmental quality and economic consideration. The energy obtained from agrowastes is a form of renewable energy and, in principle, utilizing this energy does not add carbon dioxide, which is a greenhouse gas, to the atmospheric environment, in contrast to fossil fuels [1]. Due to the lower contents of sulfur and nitrogen in agrowastes, its direct utilization as fuel in the combustion process generally generates less environmental pollution and health risk than either nuclear power or fossil fuel power. Also, biomass energy stores more easily than energy system using solar energy, which requires separate and expensive storage facilities [2].

Taiwan, located in the southeastern rim of Asia, is a densely populated island country (population density: 640 people/km^2; total area: 36 000 km^2) with only limited natural resources. The imported energy accounts for approximately 97% of the total energy supply in this subtropical country. With the rapid industrialization and economic development in the past decades, the national energy comsumption

reveals a highly increasing trend with economic growth, resulting in heavy environmental loadings and high-energy dependence [3]. In 2000, energy supply totaled 106.23 million kiloliters of oil equivalent (KLOE), in contrast to 58.57 KLOE in 1990 [4]. In recent years, the global environmental issues such as global warming and sustainable development are consecutively arousing public concerns. In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was declared in Rio De Janeiro (Brazil) followed by the Kyoto Protocol in 1997. Subsequently, developed and developing countries around the world have prevailingly addressed the mitigation strategies and policies related to greenhouse gases (GHGs) such as carbon dioxide and methane. In response to the Kyoto Protocol adopted in December 1997, Taiwan convened the National Energy Conference in May 1998. One of the most important conclusions was to increase the share of renewable energy in Taiwan's total energy supply, up to 3% in 2020. For this reason, energy strategies and policies for promoting renewable energy must be active to provide some environmental and financial/economic incentives [5]. With respect to energy policy for economic development and sustainable development, the Executive Yuan has revised and approved "The Energy Policy of the Taiwan Area", implemented by the Energy Commission under the Ministry of Economic Affairs (MOEA) [6], the primary agency responsible for industrial development and energy policy in the central government level. The relevant points of energy policy include the production of clean energy, mitigation of greenhouse gas emissions and reinforcement of renewable energy research and development (R&D).

Cellulose is the most abundant organic material in the plant-based biomass, and can be used as a source of foods, fuels and chemicals. Since bagasse from sugar mills and rice hull from rice-milling factories are the most abundant cellulosic agrowastes in Taiwan, these bioresources have been used directly (e.g. burning them for heating and electricity generation) by the thermo-chemical methods [7,8], or indirectly by bio-converting them into available liquid fuels (e.g. alcohol from sugar crops) [9]. On the other hand, the number of hogs raised in Taiwan was always maintained to be over 7 million in the past decade. The hog farms have been accompanied by vast amounts of pollution owing to the animal waste or animal-based agrowastes (i.e. feces and urine). It was suggested that the three-step treatment system (i.e. solid–liquid separation, anaerobic fermentation and activated sludge process) was considered to be very suitable for Taiwan conditions [10]. Further, the biogas generated from anaerobic fermentation has been used as an energy source for heating, cooking or electricity generation. The biogas, however, is one of the potential GHGs sources because its composition mainly includes methane and carbon dioxide, which may result in a rise in the earth's temperature (also known as global warming) [11].

Therefore, the objectives of this paper will present an updated review and innovative information on energy utilization from mass agrowastes in Taiwan. These approaches and progresses will be expected to offer cost-effective measures for other developing countries. The term agrowastes addressed in the present paper refers to the "general industrial wastes" by the definition of Waste Disposal Act in Taiwan [3]. These biomass wastes are produced from the non-household enter-

prises such as sugar mill, rice-milling factory and hog farms. The main subjects covered in this paper are listed in the following key elements:

- Definition and sources of agrowaste
- Bio-energy conversion process
- Current promotion regulations on agrowaste-to-energy
- Energy policy for waste-to-energy
- Promoting agrowaste-to-energy in progress.

2. Definition and sources of agrowaste

According to Taiwan's Waste Disposal Act (WDA) newly amended in October 2001, waste is categorized into two types: general waste (equivalent to municipal solid waste) and industrial waste [3]. The former is defined as follows (Article 2 of WDA): "these wastes include garbage, excrement and urine, animal corpses in solid or liquid form generated by households or other non-industries, which have capacity to pollute the environment". The latter is further classified into general industrial wastes and hazardous industrial wastes. The agrowaste discussed here is a label and legally treated as a waste by the government regulation for the purpose of environmental management. The government definition is therefore cited to elucidate the term, which refers to the biomass from plant material and animal waste in the agricultural processing/manufacturing enterprises. It should be noted that residues are not wastes, but rather a by-product because they are generated from the remains of a raw material during the processing [12]. Practically, they are further handled to produce more products or materials based on the resource conversion and economic consideration. For example, molasses, one of by-products from sugar manufacturing mill, is generally utilized for the production of ethanol by the fermentation process in Taiwan [13].

The agrowaste addressed in the present paper can be roughly divided into two sources: plant-based waste and animal-based waste. The former consists mainly of polysaccharides (cellulose and hemicellulose), lignin, and extractives [1], all of which are composed of carbon, hydrogen and oxygen. Trace elements like nitrogen, sulfur, chlorine and metals are also contained in these biomass wastes. On the other hand, animal-based waste consist richly of fats and proteins. Although the ratios of carbon, hydrogen and oxygen are different from those observed in the plant-based wastes, it is also made of these elements. However, the contents of nitrogen and sulfur in the animal-based wastes are generally higher than those found in the plant-based waste. Further, the plant-based waste can be defined in two main types: woody plants and herbaceous plants. The former is typically characterized by slow growth and is thus composed of tightly bound fibers, while the latter is typically perennial with loosely bound fiber. Table 1 presents the categories and energy conversion status of agrowastes in Taiwan. Table 2 shows the generation amounts of main herbaceous plant-based wastes during 1990–2000 in Taiwan [14]. Table 3 depicts number of livestock and poultry on farms at the year end dur-

Table 1
The categories and energy conversion status of agrowastes in Taiwan

Category	Moisture content	Current energy conversion	Example
Plant-based			
Woody	Low	Direct combustion	Waste woods from pulp and paper mill
Herbaceous	Medium	Direct combustion	Bagasse from sugar mill; rice husk from rice mill
Animal-based	High	Anaerobic digestion	Pig feces/urine from hog farmer

Table 2
Generation amount of main crop wastes/residues during 1990–2000 in Taiwan[a]

Year	Rice straw	Rice husk	Corn con	Corn stover	Groundnut shell
1990	1,575,733	379,089	139,169	339,436	15,595
1991	1,595,031	383,732	131,742	321,322	20,116
1992	1,428,217	343,600	138,910	338,804	18,139
1993	1,540,724	370,667	141,946	346,210	18,351
1994	1,422,368	342,193	141,571	345,295	19,340
1995	1,429,658	343,946	131,189	319,972	22,134
1996	1,332,319	320,529	136,932	333,980	19,180
1997	1,408,872	338,946	114,189	278,509	20,204
1998	1,282,819	308,620	74,578	181,897	16,398
1999	1,322,251	318,107	82,490	201,195	16,117
2000	1,315,180	316,406	73,109	178,315	18,990

[a] *Source*: [14]; unit: metric ton.

Table 3
Number of livestock and poultry on farms during 1993–2002 in Taiwan[a]

Year	Livestock			Poultry			
	Hog	Cattle	Sheep	Chicken	Duck	Goose	Turkey
1993	9,845	166	366	92,329	13,315	3,049	268
1994	10,066	164	401	97,827	12,843	3,427	215
1995	10,509	165	431	101,838	13,084	2,979	204
1996	10,698	163	429	110,535	12,977	3,021	180
1997	7,967	166	443	117,565	11,863	3,180	211
1998	6,539	165	403	120,510	11,513	3,225	229
1999	7,243	165	363	121,512	11,649	3,006	262
2000	7,495	162	315	117,885	10,624	2,821	251
2001	7,165	153	284	117,310	10,104	2,613	235
2002	6,794	149	250	118,846	10,124	2,542	191

[a] *Source*: [15]; unit: thousand heads.

ing 1993–2002 in Taiwan [15]. Table 4 lists the generation amounts of animal-based wastes (livestock wastes and poultry wastes) during 1990–2000 in Taiwan [14,16].

3. Bio-energy conversion process

Agrowastes can be converted into useful forms of energy (also called bio-energy), which belongs to one of renewable energy. Generally, the bio-energy conversion process is classified into two broad pathways: thermo-chemical and bio-chemical. Table 5 summarizes these processes from the points of energy forms, typical examples and developmental status in Taiwan. In response to the urgent need for renewable energy, there are numerous ongoing technological developments in the field of biomass energy conversion. However, only an overview is addressed here [17–20].

3.1. Thermo-chemical process

Due to the high calorific value and ultimate analyses of plant-based agrowastes listed in Table 6 [21–23], it implies that these agrowastes are potentially useful for energy utilization in the forms of combustible gas, tar oil (liquid fuel), char (solid fuel), steam, or electricity when they are processed by using thermo-chemical processes. The thermo-chemical technologies for biomass conversion are generally categorized into three options: direct combustion, gasification and pyrolysis.

Table 4
Generation amount of main animal wastes during 1990–2000 in Taiwan[a]

Year	Livestock[b]		Poultry waste[b]	Total
	Feces	Urine		
1990	7,376,830	13,035,614	4,528,453	24,940,897
1991	8,589,828	15,289,130	4,635,472	28,514,430
1992	8,341,741	14,815,005	5,293,494	28,450,240
1993	8,524,588	15,048,646	5,529,297	29,102,531
1994	8,690,449	16,250,624	5,813,177	29,885,206
1995	9,041,488	16,044,513	5,968,017	31,054,018
1996	9,168,332	16,311,014	6,388,443	31,867,789
1997	7,336,661	12,460,892	6,696,017	26,493,570
1998	6,333,057	10,406,581	6,827,158	23,566,796
1999	6,816,225	11,392,317	6,862,682	25,071,224
2000	6,957,467	11,715,601	6,730,275	25,403,343

[a] *Source*: [14,16]; unit: metric ton.
[b] Livestock mainly denotes hog; poultry includes chicken, duck etc.

Table 5
The process categories of renewable energy from biomass wastes

Transformation process	Energy form	Biomass waste/residue examples	Development status in Taiwan
Direct combustion	Hot water, steam, electricity	Rubber, agricultural wastes (e.g. bagasse), MSW[a]	Commercial installation
Pyrolysis	Bio-oil (bio-crude), charcoal, non-condensable gases	Plastics, rubber	Commercial installation
		Agricultural wastes (e.g. bagasse, rice straw, rice husks)	Research & development in lab
Alcoholic fermentation	Ethanol, gasoline fuel[b]	Sugar, molasses	Commercial installation
Anaerobic digestion	Landfill gas (methane)	MSW, pig waste	Commercial installation
Gasification	Methane, hydrogen, carbon monoxide, hot water, steam, electricity	Agricultural wastes (e.g. rice straw, rice husks, peanut shells), plastics	Pilot-scale demonstration,
Agrochemical process	Bio-diesel	Recycled frying oils	Research & development in lab
Hydrogen-producing fermentation	Hydrogen	Organic wastewaters	Research & development in lab
Supercritical fluid extraction	Liquid fuels	Agricultural wastes (e.g. olive husks)/crops (e.g. snowdrop)	Not available
Liquefaction (catalyst/hydrogen)	Liquid fuels	Wood wastes	Not available

[a] Including wood wastes and some agricultural production/processing wastes.
[b] Brazil has a successful industrial scale project for producing ethanol used as a supplement or substitute for petrol in cars.

3.1.1. Direct combustion

Combustion refers to the rapidly thermal oxidation or burning of organic materials in the presence of sufficient oxygen with the evolution of heat. The process has widely been applied on various scales to converting biomass wastes to heat and/or electricity with the utility of a steam cycle (e.g. stove, furnace, boiler, or steam turbine). It is a proven technology, although small-scale households or other non-industrial applications such as domestic cooking and space heating can be inefficient and may generate some air pollution problems. On a large-scale industrial application, biomass wastes such as sugarcane bagasse and wood waste from mills can be practically combusted in furnaces and boilers to produce process heat or steam for a Rankine cycle (steam turbine). Another approach is to co-combust with solid fuel in coal fired power plant, or municipal solid waste (MSW) incineration plants for the purpose of the higher energy efficiency than household cooking and space heating.

Table 6
Heating value and chemical analyses of typical biomass wastes

Biomass	LHV[a] (MJ/kg)	Chemical composition (dry basis)[b]					Element analysis (dry basis)[c]			
		Cellulose	Hemi-cellulose	Lignin	Extractive	Ash	C	H	O	N
Wood	18.4	47.5	19.4	24.0	7.5	1.6	47.8	5.1	45.4	0.1
Bagasse	16.2	41.3	22.6	18.3	13.7	2.9	44.8	5.4	39.6	0.4
Rice husk	15.3	31.3	24.3	24.3	8.4	23.5	41.0	4.3	35.9	0.4
Rice straw	15.3	37.0	22.7	13.6	13.1	19.8	41.8	4.6	36.6	0.7
Corn cob	17.6	40.3	28.7	16.6	15.4	2.8	46.6	5.9	45.5	0.5
Corn stover	16.5	42.7	23.6	17.5	9.8	6.8	43.7	5.6	43.3	0.6
Groundnut shell	17.5	35.7	18.7	30.2	10.3	5.9	45.8	5.5	39.6	1.6

[a] LHV denotes lower heating value (dry basis); *Source*: [21].
[b] *Sources*: [22,23].
[c] *Source*: [21].

3.1.2. Gasification

Gasification is the conversion of biomass wastes with adding steam (steam gasification) and/or hydrogen (hydrogasification) into a mixture of gaseous fractions by the partial oxidation at high temperature. The resulting product (also called producer gas) is mainly composed of carbon monoxide, hydrogen, carbon dioxide, nitrogen, water steam and C_{1-3} hydrocarbons. The product gas after pretreatment or clean-up can be used as a feedstock in the production of chemicals (e.g. methanol, gasoline), or converted into heat and electricity by direct firing in engines, turbines and boilers. In order to upgrade the energy efficiency (up to 50%), recent development has been focused on the biomass integrated gasification/combined cycle (BIG/CC).

3.1.3. Pyrolysis

Pyrolysis is generally described as the thermal decomposition of the organic components in biomass waste in the absence of oxygen at mediate temperature (about 500 °C), to yield tar (bio-oil, bio-fuel, or bio-crude), char (charcoal) and gaseous fractions (fuel gases). For convenience, there are two approaches to the conversion technology. The first approach, referred to as conventional or traditional pyrolysis, is to maximize the yield of fuel gas at the preferred conditions of high temperature, low heating rate and long gas resistance time, or to enhance the char production at the low temperature and low heating rate. Another approach referred to as flash or fast pyrolysis is to maximize the yield of liquid product at the processing conditions of low temperature, high heating rate and short gas resistance time. Due to the poor thermal stability and corrosivity in the use of the bio-crude, the liquid products still need to be upgraded by lowering the oxygen content and removing residues by means of hydrogeneration and/or catalytic cracking. Eventually, the purified bio-oil can be used as fuel in boilers, engines, or turbines, or processed into refineries as a feedstock also being considered.

3.2. Bio-chemical process

Two main processes, anaerobic digestion and alcoholic fermentation, are widely utilized for energy conversion of biomass with high moisture content such as animal manure and bio-sludge. Basically, these processes are based on biological actions that convert semi-solid or liquid biomass into a biogas or liquid fuel (i.e. ethanol).

3.2.1. Anaerobic digestion

Anaerobic digestion is the conversion or degradation of organic wastes through microbial actions in the absence of oxygen to reducing gases (biogas) that mainly consist of methane and carbon dioxide and contain various trace components such as hydrogen sulfide, acids and thiols. A typical example is the landfill gas (LFG) from the MSW buried in sanitary landfill sites. The collected LFG, which generally consists of up to 50% methane, can be purified and then burned in engines or turbines to produce heat and electricity. Practically, the biogas is commonly produced by using animal manure in an airtight container (digester). Due to the high heating

value (5400–6000 kcal/Nm^3) of biogas, the biogas thus generated can be directly combusted in burners for cooking, or used as gas fuel in internal combustion engines to generate electricity, or further upgraded to natural gas quality by the removal of carbon dioxide and hydrogen sulfide.

3.2.2. Alcoholic fermentation

It is well known that the fermentation is commercially applied in the production of alcoholic wines from sugar crops (e.g. sugarcane, molasses) and starch crops (e.g. rice, wheat). Ethanol thus produced from biomass material in the presence of organism (e.g. yeast) provides a high quality fuel for storage and transport. It should be noted that the biochemical conversion of woody wastes is more difficult for the fermentative degradation and need first to be broken down by acidic or enzymatic hydrolysis because of the presence of longer-chain polysaccharides. On the basis of energy utilization, product ethanol after distillation purification can be used as a supplement or substitute for petrol or gasoline in cars. Also, biomass materials for alcoholic fermentation are generally agricultural production/processing residues or energy crops. Molasses, a by-product of sugar-manufacturing process, has been industrially bio-converted for the production of ethanol [9].

4. Current promotion regulations on agrowaste-to-energy

In Taiwan, the promotion regulations related to waste-to-energy are mainly based on the Statute for Upgrading Industries (SUI), which was originally promulgated and became effective in December 1990 and was thereafter revised in January 1995, January 2002 and February 2003, respectively. According to the newly revised SUI, important features concerning the aspects of waste-to-energy include as follows:

1. To provide the financial incentives for any of the listed purposes (e.g. employing new and clean energy), service life of instruments and equipment purchased by a company may be accelerated to two years. However, provided there is any post-depreciation residual value during the accelerated service life, assets depreciation may continue in one year or several years within the service life of such assets as specified in the Income Tax Law until depreciation is fully made (Article 5).
2. To meet the requirement for industrial upgrading, an enterprise may credit 5–20% of the amount of fund disbursed for any of the listed purposes (e.g. the fund invested in the equipment or technology used for harnessing new and clean energy) against the amount of profit-seeking enterprise income tax payable for the then current year (Article 6).
3. In order to encourage the incorporation or expansion of the newly emerging, important and strategic industries (thereafter announced by the Ministry of Economics Affairs in December 2001, including biogas generation equipment, and emerging/clean energy utilization service) that can produce substantial benefits to economic development, an investor (profit-seeking enterprise or individual),

who subscribes to the registered stocks issued by the company and has held such stocks for a period of three years or longer, may deduct the profit-seeking enterprise income tax or the consolidated income tax up to 20 and 10% of the price paid for acquisition of such stocks for profit-seeking enterprise and individual, respectively (Article 8).
4. The Executive Yuan (Cabinet) shall establish a development fund for low interest loans and make use of such development fund for the listed purposes (e.g. reduction of greenhouse gas effects) (Article 21).
5. In order to advance technologies, enhance R&D activities and further upgrade industries, the relevant central government agencies in charge of end enterprises may promote the implementation of industrial and technological projects by providing subsidies to such R&D projects (Article 22-1).

Under the authorization of Article 6 of SUI, the regulation, known as "*Regulation of Tax Deduction for Investment in the Procurement of Equipments and/or Technologies by Energy conservation, or emerging/Clean Energy Organizations*", has first been promulgated by the Ministry of Finance (MOF) in July 1997, and thereafter revised in November 1999, July 2000, September 2001 and January 2003, respectively. These specified organizations shall be granted credits on the profit-seeking enterprise income tax for the current year if they use these equipments and/or technologies by themselves according to the following percentages of total purchase cost (>NT$ 600 000) in the current year:

- 13% for energy conservation or emerging/clean energy utilization equipments.
- 10% for energy conservation or emerging/clean energy utilization technologies.

If the profit-seeking enterprise income tax for the current year is not enough to be granted a tax deduction for investment, they may deduct the tax in the next 4-years for their profit-seeking enterprise income taxes.

Besides the promotion incentives from SUI, under the authorization of Article 39 of the newly-revised Waste Disposal Act (WDA), the responsible agencies at the central government level have promulgated the regulations (i.e. "Regulations Governing the Permitting of Industrial Waste Reuse") related to industrial waste reuse by the Ministry of Economic Affairs (MOEA) in January 2002. According to the definition of the regulation, industrial waste can be directly reused without compliance with the requirements of intermediate treatment and final disposal. The term "reuse" should refer to the industrial waste reused by the waste producers themselves, or sold, transferred or entrusted to others for reuse as raw material, material, fuel, engineering filler, soil modification, reclaimed land, land-fill or for other approved purposes. Of these announced wastes, scrap woods (whole/part) and bagasse can be legally permitted them to reuse as fuel [3].

With the funding supports of Energy Commission under the Ministry of Economics Affairs (MOEA) and National Science Council (NSC), many researchers' science and technology projects place emphasis on agrowaste-to-energy at research and development (R&D) laboratories. For example, the Energy and Resources

Laboratory of the Industrial Technology Development Institute (ITRI) acts as a consulting group to assist industries in adopting and implementing energy utilization from gasification of agro-waste (i.e. rice husk) [24]. In the authors' laboratory, which is in Chia Nan University of Pharmacy and Science (Tainan, Taiwan), research has been conducted on fast pyrolysis for local mass agro-wastes such as rice husk, rice straw, bagasse and coconut shell. It has been demonstrated that the advanced process can enhance the yield of bio-crude for the purpose of in-situ production and ease storage [25].

5. Energy policy for waste-to-energy

Due to the impact of energy crises and changes in the energy situation in the 1970s, "The Energy Policy of Taiwan Area" was first promulgated in April 1973 under the approval of Executive Yuan. Thereafter, the energy policy was further revised in response to dramatic changes in the domestic and international energy situations, economic situations and environmental issues. In May 1998, a National Energy Conference was held in Taipei city for the purposes of formulating strategies and measures in response to the impact of the United Nations Framework Convention on Climate Change (UNFCCC) and to the pursuit of a sustainable development between economic, energy and environment (3 E) in Taiwan. Renewable energy is a sustainable and clean energy derived from natural resources. It was thus concluded that the utilization of new and clean energy should be actively promoted to achieve a 3% target share for renewable energy in terms of total energy supply by 2020 [6].

In order to further integrate and coordinate the tasks of promoting the continued use of renewable energy, the Executive Yuan adopted the "Renewable Energy Development Plan" in January 2002. The Council for Economic Planning and Development will be in charge of coordinating the efforts of central government authorities in promoting renewable energy. For example, researchers at universities and national laboratories are carrying out mission-oriented projects including waste-to-energy and biogas utilization technologies under the funding supports of the National Science Council (NSC) and the Ministry of Economics Affairs (MOEA). In the near future, a new law called "Statute for Renewable Energy Development" will be enacted to establish a legal environment for renewable energy and to facilitate the sustainable utilization of renewable energy. Among these promotion measures, procurement charge of electricity from renewable energy will be guaranteed at fixed rate of NT$ 2.0/kW-h (US$ 0.06/kW-h) by this law [5]. Also, subsidy will be provided to reduce the capital costs of some renewable energy utilization equipments. The law aims at the total promotion amount of 3300 and 6500 MW in 2010 and 2020, respectively.

6. Promoting agrowaste-to-energy in progress

Since Taiwan's entry into the World Trade Organization (WTO) in 2001, the sugar, rice and livestock (e.g. hog) markets have been totally open to other countries. These goods, however, are still dependent on domestic production. As expected, bagasse and rice husk from mills, and piggery wastes from swine farms, are inevitably generated and can be considered as major sources of biomass suitable for large-scale industrial utilization in Taiwan. Of these agrowastes, bagasse has been directly combusted in the boiler of sugar mill. Swine wastes and rice husk can both be converted into products of higher energy contents by anaerobic fermentation and gasification, respectively. In this section, we present the biomass energy utilization of these agrowastes in progress.

6.1. Bagasse energy from sugar mill

Taiwan lies in the subtropical and tropical zones and has a total annual rainfall of 2000–2500 mm. The climate is very favorable for the cultivation of sugarcane. Taiwan Sugar Corporation (TSC), the only manufacturer in Taiwan, has reorganized its production strategy since the early 1980s in response to the international sugar market. Based on the data [7], annual sugar production was 468 000 metric ton while total bagasse generation thus produced was approximately 1 520 000 metric ton per year in 1993–1994. According to the business evaluation in TSC, the domestic production capacity of sugar is planned to be maintained at 120 000 metric ton per year based on the remaining four sugar mills and one sugar refinery. Therefore, the amount of bagasse from sugar mills will rapidly diminish in the coming years. Due to the high-energy content (about 4000 kcal/kg, dry basis) in the cellulosic waste, direct combustion was successfully adopted by all the sugar mills in TSC as shown in the typical diagram of sugar manufacturing (Fig. 1) [26]. However, it is noted that the thermal process has the potential of emitting a diverse type of air pollutants to the environment. These potential emissions may arise from compounds (e.g. heavy metals) present in the waste stream, are formed as a part (e.g. particulate and acid gases) of the normal combustion process, or are formed as a result (e.g. carbon monoxide) of incomplete combustion. Table 7 lists stack emission standards of air pollutants from stationary sources in Taiwan, which was first issued by Taiwan EPA in April 1992.

The energy utilization was commonly carried out in the boiler. Sometimes it was converted into steam turbine for electricity generation or it directly heated the processes such as multi-effect evaporator and juice heater. Based on the preliminary evaluation by authors, the total economic and environmental performances of energy utilization from the bagasse are estimated according to 120 000 metric ton per year of sugar production capacity as follows:

- Agrowaste reduction: 390 000 metric tons/year (based on 3.25 metric ton bagasse/metric ton sugar)
- Electricity generation: 5.4×10^8 kW-h/year (based on 4000 kcal/kg heating value, 30% energy efficiency)

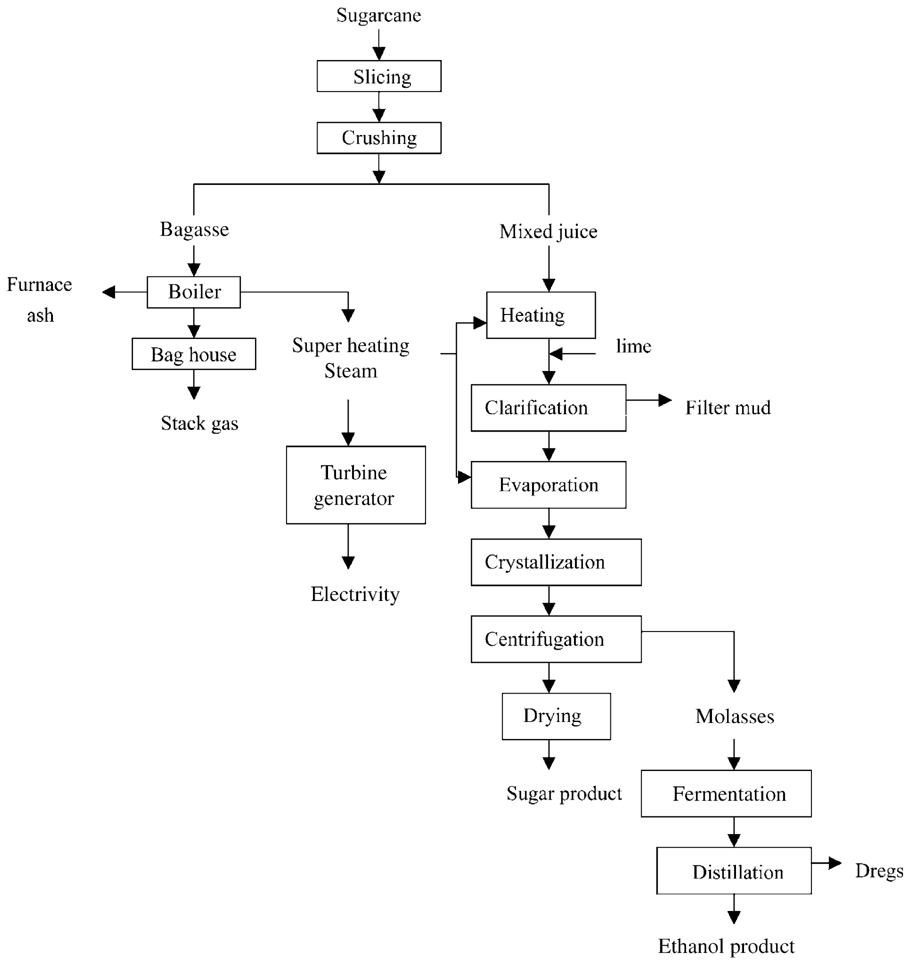

Fig. 1. Typical diagram of sugar manufacturing in Taiwan.

- Equivalent electricity charge saving: US$ 4.0×10^7 /year (based on US$ 0.074/kW-h)
- Equivalent carbon dioxide mitigation: 4.9×10^5 metric ton/year (based on 1.25 metric tons equivalent carbon dioxide mitigation/metric ton bagasse).

6.2. *Biogas energy from piggery waste*

Based on the survey data of Taiwan's Council of Agriculture (COA) [15], the total heads of hog were approximately 6.8 millions at the end of 2002 (Table 3). The piggery wastes (including feces and urine) inevitably generated from the hog farms contain a high content of organic matters such as proteins, hydrocarbons

Table 7
Stack emission standards of air pollutants from stationary sources in Taiwan

Item	Standards[a]	Comment
Opacity (%)	20%	Not available for small-scale (<2500 cc) internal engine
Particulate matter (mg/Nm^3)	Conversion by effluent rate: $C=1860.3\ Q^{-0.386}$ ($25 \leqq C \leqq 500$) Q: effluent rate (Nm^3/min)	
Sulfur oxides (as sulfur dioxide) (ppm)	100 (combustion process, gas fuel) 300 (combustion process, liquid fuel) 300 (combustion process, solid fuel) 650 (sources excl. combustion process)	
Sulfuric acid droplet (mg/Nm^3)	100 (sulfuric acid plant) 200 (sources excl. sulfuric acid plant)	
Nitrogen oxides (as Nitrogen dioxide) (ppm)	150 (combustion process, gas fuel) 250 (combustion process, liquid fuel) 350 (combustion process, solid fuel) 250 (sources excl. combustion process)	Only available for new emission sources (Facility was installed after Apr. 10, 1992)
	350 (combustion process, gas fuel) 400 (combustion process, liquid fuel) 500 (combustion process, solid fuel) 500 (sources excl. combustion process)	Only available for existing emission sources (Facility was installed prior to Apr. 10, 1992)
Hydrogen chloride	80 ppm or $\leqq$1.8 kg/hr	
Chlorine (ppm)	30	
Carbon monoxide (ppm)	200	
Total fluorides (as F^-) (mg/Nm^3)	10	
Hydrogen sulfide (ppm)	100 (directly vented to atmosphere) 650 (inlet conc. prior to combustion treatment)	
Lead and its compounds (mg/Nm^3)	10	
Cadmium and its compounds(mg/Nm^3)	1	
Asbestos and its compounds (mg/Nm^3)	Invisible by naked eye	
Vinyl chloride (ppm)	10	

[a] Concentration calculation of air pollutant in the stack gas must be based on 273 K, 1 atm and dry volume of undiluted effluent. Also, 6% O_2 (oxygen content) is referred as correction baseline.

and fats. For the purpose of avoiding water quality deterioration (e.g. eutrophication), the animal waste must be treated prior to the discharge into receiving waters. Theoretically, a sustainable way to treat the animal waste is to recycle the biomass and return it to the land soil. The odor and receiving water (e.g. river) pollution, however, have been urgent environmental issues.

Due to the advances and advantages of anaerobic fermentation process, biochemical technology has been extensively investigated and successfully applied to

the treatment of the piggery waste by the Taiwan Livestock Research Institute since the mid-1970s [27]. The horizontal anaerobic digester made with red mud plastic (RMP) was originally developed for treating the animal wastewater. After many studies and modifications, the three-step piggery wastewater treatment system was recommended to the hog farm, as shown in Fig. 2. The biological treatment system is simply described as follows: (1) The first-step is the solid-liquid separation by screening method. After the operation, the solid material is collected for composting. (2) The second-step is horizontal anaerobic fermentation. During the anaerobic treatment, biogas is thus generated as a useful fuel for stove heating, piglet warming, water pump, electricity generation, etc. The single-stage fermentation process was thereafter separated into two sections in order to enhance the operation performances. (3) The third-step is an activated sludge process in response to the strict regulation of effluent standards in Taiwan. Further, the sequencing batch reactor was studied for the removal of nitrogen and phosphorus from the piggery wastewater [28]. The preliminary results indicated that removing efficiencies of them reached 60–80%.

Under the normal operation at 35 °C, loading rates of 1290–9240 mg volatile solid/liter/day and hydraulic retention time (HRT) of 2–12 days, the high removal efficiencies (69–90%) of chemical oxygen demand (COD) can be significantly per-

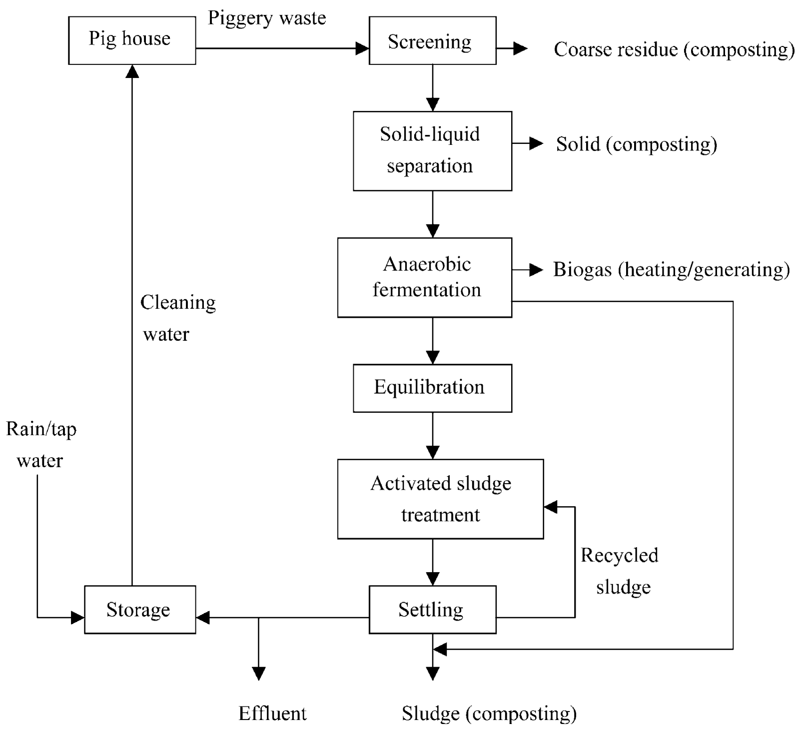

Fig. 2. Diagram of three-step piggery waste treatment process in Taiwan.

formed in the three-step wastewater treatment system [27]. Also, the production rate of biogas ranging 0.97–2.79 l/l (fermentor)/day with the methane contents of 61.9 and 53.1%, respectively, was generated. It should be noted that the unpurified biogas is corrosive because of 33–38% carbon dioxide and 0.20–0.33% hydrogen sulfide in the humid production gas. Therefore, the removal of non-methane gas constituents should be considered prior to the energy utilization. There are several methods to purify the fermented biogas; the spirulina culture absorption method was successfully developed by the Taiwan Livestock Research Institute [29]. The purified biogas contains 99% methane, which can be safely stored in a RMP bag or compressed cylinder after dehydration and condensation.

Although the high-energy content (>5000 kcal/m^3 based on 50–80% methane) of biogas from the anaerobic fermentation can be utilized as gas fuel for electricity generation, there were some barriers to the promotion such as in-plant use (not used as pipe-line gas) and high costs. Since the mid-1990s, in order to mitigate greenhouse gas emissions from biogas based on United Nations Framework Convention on Climate Change (UNFCCC), the Taiwan government was active in promoting the related enterprises to construct biogas-electricity generation unit under the encouragement of national energy policy [6]. Based on the preliminary evaluation by the authors, the total economic and environmental performances of biogas energy utilization from the piggery waste and wastewater are estimated according to 7 million heads of hog as follows:

- Biogas production capacity: 6.4×10^8 m^3/year (based on 0.25 m^3/day/head)
- Electricity generation: 9.1×10^8 kW-h/year (based on 0.7 m^3 biogas/ kW-h)
- Equivalent electricity charge: US\$ 6.7×10^7/year (based on US\$ 0.074/ kW-h)
- Equivalent methane mitigation: 2.5×10^5 metric ton/year (base on 60% methane in the biogas)
- Equivalent carbon dioxide mitigation: 6.0×10^6 metric ton/year (based on global warming potential with a 100-year time horizon of $CH_4 = 23$, relative to GWP of $CO_2 = 1$) [30].

6.3. Syngas energy from rice husk

Due to the warm climate and extensive cultivation, rice has been used as a staple for a hundred years in Taiwan. In recent years, while the annual production of rice trends to decrease, there is still ca. 1.7 millions in 2002 [15]. It means that the rice husk, which is a major by-product of the rice-milling industries, was abundantly generated at the annual average production of over 300 000 metric tons as shown in Table 2. However, only small fraction of the agrowaste produced in Taiwan was used for poultry feed or as filter materials. Most of it was arbitrarily dumped into fields [31], disposed of landfills, or reused as fuel for household cooking and paving materials in the animal husbandry in response to the environmental regulations of solid waste management [8]. Like other biomass wastes, rice husk contains a high amount of organic constituents and possesses a high-energy content as shown in

Table 6. Therefore, it can be recognized as a potential source of renewable energy. In Taiwan, developments in the pilot-scale gasification of rice husk have been demonstrated as one of the effective technology options in the production of hydrogen-rich synthesis gas [31–34]. This thermo-chemical process provides a potentially feasible method for utilizing the agricultural waste into high-energy gas fuel, which can be further converted into electricity in the generation power system.

In order to upgrade the demonstrated process to commercial-scale rice husk gasification plant, the farmers' association of Yulin county, which is located in central Taiwan and also has the highest production of rice husk in Taiwan, planned to build the first gasification-generation plant according to the feasibility study of the Energy and Resources Laboratories of Industrial Technology Development Institute (ITRI) in 2002. With the investment of NT$ 150 million (US$ 4.5 million), the project was expected to gain the following benefits based on the annual treatment capacity of ca. 66 000 metric tons: NT$ 33 million net profit and ca. 20 000 metric tons black ash (a by-product, which can be reused as organic fertilizer, or as a thermo-insulating agent in steel-making). The gasification project not only solves the agrowaste treatment/disposal problems for local governments and industries, but also establishes an available foundation for renewable energy utilization in Taiwan by benefiting the energy supply sources, which currently rely on imports almost exclusively.

Based on the preliminary evaluation by the authors, the total economic and environmental performances of syngas energy utilization from the rice husk gasification and electricity generation are estimated according to the annual production of 1 500 000 metric tons of rice as follows:

- Agrowaste reduction: 300 000 metric tons/year (based on 0.2 metric ton rice husk/metric ton rice)
- Electricity generation: 4.5×10^8 kW-h/year (based on 3600 kcal/kg heating value, 30% energy efficiency)
- Equivalent electricity charge saving: US$ 3.3×10^7/year (based on US$ 0.074/kW-h)
- Equivalent carbon dioxide mitigation: 3.4×10^5 metric ton/year (based on 1.13 metric tons equivalent carbon dioxide mitigation/metric ton rice husk).

7. Conclusions and prospects

In recent years, energy supply/consumption related to global warming has been the focus of environmental legislation and economic development for pursuing sustainable development and creating green energy in Taiwan. Since May 1992, the Executive Yuan established the ministerial-level inter-departmental agencies (i.e. Global Change Working Group and Committee on Global Change Policy) to coordinate activities related to the United Nations Framework Convention on Climate Change (UNFCCC) and other environmental issues. In August 1997, it was further expanded to form the National Council for Sustainable Development.

From the historical information and data presented here, It is also obvious that the energy utilization from agricultural wastes or agrowastes has been relatively attractive under the policy encouragement and economic feasibility. During this period, the environment, economic and energy (3E) policies have switched from regulation establishment, information and technology transfer, and training and education in the early stage, to provision of assistance incentives and financial support to industries harnessing renewable energy including agrowaste-to-energy and biogas energy. It is undoubtedly expected that the Statute for Renewable Energy Development under enactment will further drive the gradual displacement of traditional fuels and fossil energy because of crude oil/natural gas shortage, nuclear waste safety and the high costs of maintaining the clean environment. To greatly promote energy utilization from biomass wastes in Taiwan, the following measures are recommended and enhanced:

- Give priority in economic and technological assistances to small enterprises and medium-sized energy technology services.
- Require high energy consumption industries (e.g. paper and pulp, petrochemical and cement manufacturing) to make net energy reduction by combusting biomass wastes partly.
- Set up the national laboratory for renewable energy research and development like National Renewable Energy Laboratory (NREL) in the USA.
- Educate students at college/university with integrated and prospective courses, such as "green energy or renewable energy" in the department of agricultural engineering, agricultural mechanical engineering, chemical engineering or mechanical engineering.
- Combine "green" costs (e.g. carbon tax) with accounting system of enterprise or business.
- Grant certificates of ISO-14000 series to industries utilizing energy from wastess; that is, the waste-to-energy is considered as one of environmental performances.
- Focus waste-to-energy on biogas, not on biomass combustion from the viewpoint of net greenhouse gas mitigation and air quality attainment.
- Develop pilot-scale bio-technology for hydrogen generation from high-organic content industrial wastewater because hydrogen energy has been recognized as the most clean fuel, without greenhouse gas emission.
- Research bench-scale catalytic reaction technology for hydrogen production from renewable biomass products like sugars and alcohols with the help of a specified catalyst.
- Demonstrate commercial feasibility on utilizing waste food oils as raw materials of bio-diesel oil, which has been considered as liquid fuel in place of diesel oil.
- Promote the cultivation of energy crops such as sugarcane (for the production of ethanol by alcoholic fermentation) and sunflower (for the production of seed oil by the mechanical extraction).
- Extend other mass biomass wastes (e.g. coconut shell and corn cob) for energy utilization.

Acknowledgements

This research was partly supported by NSC (National Science Council), Taiwan, under contract number NSC 92-2623-7-041-001-ET.

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